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Environmental Conditions in the Labrador Sea in 2005

by

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Abstract

Overall, 2005 was a very mild year in the Labrador Sea, similar to 2004. Annual mean 2005 patterns in sea surface temperature and sea-air heat flux both reflected mild conditions in 2005, with some differences in spatial structure compared to 2004. Conditions were somewhat cooler to the north and warmer to the south in 2005. The 16th annual occupation of the AR7W Labrador Sea section from late May to early June 2005 showed a continuation of the recent trend to warmer conditions in the upper layers of the west-central Labrador Sea. Salinities remained high, though slightly lower in 2005 than in 2004. Altimetric measurements showed increases in sea level in the west-central Labrador Sea that closely matched the steric changes seen in the hydrography. Warm and saline Irminger Atlantic Waters were plentiful in the north-eastern Labrador Sea in both May 2004 and May-June 2005. There appears to have been only shallow convection during the winters of 2004/2005, similar to the previous winter.

Introduction and Summary

Labrador Sea hydrographic conditions depend on a balance between heat lost to the atmosphere and heat gained from warm and saline Atlantic Waters carried northward into the Labrador Sea by the West Greenland Current. Severe winters under high North Atlantic Oscillation (NAO) conditions lead to greater cooling: in exceptional cases, the resulting increases in the surface density can lead to convective mixing of the water column to depths of 2 km. Milder winters under low NAO conditions lead to lower heat losses and an increased presence of the warm and saline Atlantic Waters. A sequence of severe winters in the early 1990s led to the most recent period of deep convection, which peaked in 1993-1994. Recent winters have been generally mild.

Figure 1 shows a map of Labrador Sea and surrounding land areas. The map shows the locations of selected meteorological stations discussed below, the position of Ocean Weather Station Bravo which operated in the area from 1963 to 1974, and stations locations for the annual AR7W surveys. The circled area in the west-central Labrador Sea marks the region where convection to depths as great as 2 000 m was observed during the cold period of the early 1990s (Lazier *et al.*, 2002). Wintertime convection to depths as little as 200 m and as great as 1 500 m was observed in the OWS Bravo record (Lazier, 1980).

This report draws on a number of sources of environmental information to characterize conditions in the Labrador Sea during 2005.

Annual mean surface air temperatures from representative land stations bordering the Labrador Sea were about 2°C warmer than normal in 2005, similar to conditions in 2004 and continuing a decade-long period of warmer than normal conditions. Many winter months during recent years show monthly average surface air temperatures more than 5^{o}C warmer than normal.

Mean 2005 sea surface temperatures from the UK Met Office Hadley Centre HadISST 1.1 Global Sea Surface Temperature data were more than 1^{o}C warmer than normal in the Labrador Sea and adjacent northwest Atlantic, similar to conditions in 2004. Relative to 2004, there was a slight cooling in the northern Labrador Sea and a warming to the southeast.

Annual mean sea-air heat fluxes in the west-central Labrador Sea from the NCEP/NCAR Reanalysis project have been lower than normal since 1998. The 2005 annual mean was slightly higher than the previous year's but still the third lowest since 1987. The 2005 value of 44 W/m^{2} was 23 W/m^{2} lower than the 30-year mean for 1971-2000 of 66 W/m^{2}, representing a one-third reduction from normal conditions.

Sea level in the west-central Labrador Sea based on TOPEX/POSEIDON and JASON-1 altimetry was nearly 8 cm higher in 2005 than during the cold period 1993-1995. Most of this change can be related to changes in hydrographic conditions. There has been relatively little change in annual-mean sea level during the past eight years. Mean sea level in the southern Labrador Sea and adjacent North Atlantic was slightly higher in 2005 than in 2004, but in the northern Labrador Sea this pattern was reversed.

The 16th annual Fisheries and Oceans Canada AR7W survey took place from late May to early June 2005. Between 1990 and 2005 the upper layers of the Labrador Sea have become warmer and saltier. Changes in temperature and salinity averaged over the upper 150 m during this period amount to about 1^{o}C and 0.1 respectively.

The upper 2 000 m of the water column in the west-central Labrador Sea have become steadily warmer over the past six years. By this measure, conditions in 2005 were the warmest in the 16 years of annual AR7W surveys. Salinity has shown a more complex behaviour during this time period. For the past four years, salinity has been higher than during the previous decade, with conditions in 2005 slightly fresher than in 2004. Density changes during the past few years have been relatively small, with changes linked to temperature and salinity nearly in balance.

The 2005 survey encountered warm and saline waters in the offshore branch of the West Greenland Current, with maximum salinities greater than 34.95.

The 2005 observations suggest that vertical mixing in the west-central Labrador Sea during the winter of 2004-2005 was confined to the upper 700 m and restricted to potential density anomalies of less than approximately 27.72 kg/m^{3}.

Results and Discussion

General environmental indicators

Surface air temperature

Figure 2(a) shows time series of annual mean surface air temperature anomalies for 1960-2005 relative to the 30-year 1971-2000 normal for Cartwright, Labrador; Iqaluit, Nunavut; and Nuuk, Greenland. The Cartwright and Labrador data were obtained from Environment Canada while the Nuuk data were obtained from the Danish Meteorological Institute, largely from Cappelen *et al.* (2005). All three stations showed temperatures continuing about 2^{o}C warmer than normal in 2005. Figure 2(b) shows time series of monthly mean surface air temperature anomalies for 2003-2005 for these three stations. The normal annual average air temperature at Iqaluit is more 9^{o}C colder than at Cartwright and about 8^{o}C colder than at Nuuk, but the magnitude and patterns of variability at these three stations bordering the Labrador Sea are remarkably similar. At each site, the annual mean temperature was 1-2˚C warmer than normal over the past three years. The greatest variability occurs during winter months. Warm conditions were observed in January and February 2005 at all three sites: monthly mean temperatures were about 3^{o}C warmer than normal at Cartwright and more than 5^{o}C warmer than normal at Iqaluit and Nuuk.

Sea surface temperature

Monthly averages sea surface temperature (SST) data for the Labrador Sea were extracted from the global HadISST1 data set produced by the UK Met Office Hadley Centre on a 1-degree latitude-longitude grid. Figures 3(a) and 3(b) show maps of SST anomaly relative to the 30-year normal period 1971-200 for 2004 and 2005. The 2004 and 2005 anomaly maps both show values more than 1^{o}C warmer than normal. Figure 3(c) shows the change from 2004 to 2005. SST values in the west-central Labrador Sea were virtually identical for 2004 and 2005. Conditions were slightly cooler in the northern Labrador Sea, but warmer to the south and east. Figure 3(d) shows a time series of annual SST anomalies averaged over nine grid points centred at 56.5N, 52.5W. The normal value is 4.34^{o}C. Annual mean SST at this location has been warmer than normal since the mid-1990s. The 2004 annual mean was a record high for post-1960 conditions. The 2005 value was virtually identical to the 2004 value.

Sea-air heat flux

On an annual average, the Labrador Sea loses heat to the overlying atmosphere. The greatest heat losses occur in January and February. Monthly-averaged air-sea flux fields are available from the co-operative Reanalysis Project (Kistler *et al*., 2001) of the U.S. National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR).

Figure 4(a) shows a map of 2004 mean NCEP Reanalysis sea-air heat flux anomalies for the Labrador Sea. Positions of the NCEP grid points are superimposed on the map. Figure 4(b) shows a similar map of 2005 mean sea-air heat flux anomalies. The anomalies are computed relative to a 1971-2000 normal. The anomalies in the central Labrador Sea show similar values 20-30 W/m^2 less than normal for both 2004 and 2005.but the 2005 map features an area of reduced heat flux south of Greenland. A map of the change in annual mean sea-air heat flux from 2004 to 2005 in Figure 4(c) shows that this feature is part of a notable reduction in annual mean heat loss in the northern Labrador Sea. Figure 4(d) shows a time series of annual mean sea-air heat flux anomaly in the west-central Labrador Sea at the NCEP Reanalysis grid point at 56.2N, 52.5W. The normal value is 66 W/m^2. Annual mean heat losses at this location have been less than normal for the past eight years. The 2005 annual mean of 44 W/m^2 was slightly greater than the 39 W/m^2 value for 2004 but was still the third lowest since 1987.

Sea level

The French SSALTO/DUACS group uses TOPEX/POSEIDON and JASON-1 altimetric sea level measurements to produce weekly gridded Maps of Sea Level Anomalies (MSLA) with near-global geographic coverage on a $1/3^{o}$ Mercator grid. These are distributed by the French AVISO group with support from the French national space agency CNES. Data coverage begins with the TOPEX/POSEIDON mission in late 1992 and continues to the present. The gridded MSLA are produced by a statistical interpolation that is most reliable at points close to the measurements (Le Traon, *et al*., 1998).

Figure 5(a) shows a map of annual mean Labrador Sea sea level anomaly (SLA) for 2004 from this source annotated with selected AR7W stations positions. The original MSLA product gives anomalies with respect to the 1993-1998 mean but here they are shown relative to the 1993-2005 mean. Figure 5(b) shows the same field for 2005. The patterns are similar for the two years. Figure 5(c) shows the change in annual mean SLA from 2004 to 2005. There was a slight decrease in sea level in the northern Labrador Sea and a slight increase in the southern Labrador Sea and the adjacent North Atlantic. Figure 5(d) shows a time series of annual mean SLA from a spatial average over 25 grid points centred at 56.7N, 52.3W near an orbit crossover point. Sea level showed a marked rise at this location from the mid-1990s to 2000 but has remained relatively constant since then. The time series shows a rise in sea level of about 0.01 m from 2004 to 2005, consistent with the difference map in Fig. 5(c).

AR7W Hydrography

Since 1990, Ocean Sciences Division at the Bedford Institute of Oceanography has carried out annual occupations of a hydrographic section across the Labrador Sea (Fig. 1). The section was designated AR7W (Atlantic Repeat Hydrography Line 7) in the World Ocean Circulation Experiment (WOCE). This effort continues as a regional monitoring and research program with associated chemical and biological components that contributes to the

Climate Variability (CLIVAR) component of the World Climate Research Programme (WCRP) and the international Global Climate Observing System (GCOS).

The 31 AR7W stations shown in Fig. 1 were occupied during the period May 29 – June 3, 2005 on CCGS Hudson Mission 2005016 under the scientific direction of Dr Allyn Clarke and Dr Glen Harrison. The section spans approximately 880 km from the 130 m contour on the inshore Labrador shelf to the 200 m contour on the West Greenland shelf. Sea ice sometimes limits coverage at the ends of the section but light ice conditions were encountered in 2005 and all planned stations were occupied.

A contoured gridded section of potential temperature from the 2005 survey is shown in Fig. 6. Along-section distance in kilometres increasing from southwest (Labrador) to northeast (Greenland) is used as the horizontal coordinate. The four stations within the 320-520 km distance range are chosen to represent conditions in the west-central Labrador Sea.

Notable in the upper levels of Fig. 6 are cold waters (<2^{o}C) over the Labrador Shelf associated with the Labrador Current and similarly cold waters in the upper few hundred metres over the outer edge of the West Greenland shelf associated with the inshore branch of the northward-flowing West Greenland Current. Warmer waters (>4^{o}C) in the upper 500 m of the water column over the West Greenland slope are associated with the offshore branch of the West Greenland Current. Stations and depth ranges with Irminger Mode Water properties following Buch (2000) (potential temperatures between 4^{o}C and 6^{o}C and salinities between 34.85 and 34.95) and Irminger Atlantic Water properties following Lee (1968) (potential temperatures between 4^{o}C and 6^{o}C and salinities between 34.95 and 35.10) are highlighted in Fig. 6.

In the central Labrador Sea, water at depths between 600 m and 1200 m below the seasonal thermocline has reduced vertical temperature gradients that mark vertically-mixed Labrador Sea Water (LSW) formed by winter convection in recent years. The LSW layer creates a relative minimum in potential temperature with core values near 3.2-3.3^{o}C. The section plots are annotated with the pressure of this relative minimum in potential temperature. The LSW layer extends over much of the section, but it is most prominent in the west-central Labrador Sea. The Irminger Waters in the upper 500 m on the Greenland side are notably warmer than waters at the same depths on the Labrador side. Denser components of the warm and saline Irminger Water influence a layer centred at about 1 500 m below the LSW with a relative maximum in potential temperature near 3.4^{o}C. The pressure of this intermediate-depth potential temperature maximum is also marked in Fig. 6.

Changes in upper level properties

Near-surface seasonal warming is apparent in Fig. 6. There is a regular upper ocean seasonal cycle in both temperature and salinity in the Labrador Sea, with the strongest changes concentrated in the upper 150 m of the water column. Survey times during the 16-year period varied from late May to late July. Climatological hydrographic data from the U.S. National Ocean Data Center (Conkright *et al.*, 2002) were used to model seasonal changes in 0-150 m potential temperature and salinity and remove them from the AR7W survey data. Figures 7(a) and 7(b) show time series of the resulting deseasoned 0-150 m potential temperature and salinity for stations in the 320-520 km distance range for the 16 spring and early summer AR7W occupations from 1990 to 2005. Standard deviations of individual station values for each survey are indicated on the plots. The 2005 anomalies are 0.7^{o}C in potential temperature and 0.08 in salinity relative to the 1990-2005 mean.

Interannual changes in winter convection

Figure 8 gives an overview of interannual variability from AR7W surveys since 1990. It shows a time series of the pressure on selected potential density anomaly surfaces from average profiles in the 320-520 km distance range for each survey as a function of the median station time. This is an update of Figure 4 in Lazier *et al*. (2002).

The deep convection of the early 1990s is reflected in the 1993-1995 maximum in the separation of the 27.77 and 27.79 kg/m^3 potential density anomaly surfaces bounding the deeper shaded layer in Fig. 8. The volume of water in this potential density range decreased steadily from 1995 to 2000. Pressures corresponding to the minimum potential temperature in the 27.77-27.79 kg/m^3 layer for each survey are noted in the figure. The prominent relative minimum in potential temperature in this layer created by the deep convection that peaked in the winters of 1992-1993 and 1993-1994 persists until at least 1999. Changes in the separation of these isopycnals have been small since 2000.

Starting in 1999 or 2000 and especially from 2001 to 2003 there was an increase in the separation of isopycnals with potential density anomalies in the range 27.72-27.75 kg/m^3 that define the shallower shaded layer in Fig. 8. In 2000, this layer developed a prominent relative minimum in potential temperature with core potential temperature 3.2^{o}C, salinity 34.83, and potential density anomaly 27.73 kg/m^3. A relative minimum in potential temperature is also present in 2002 and 2003 at increasing values of potential density anomaly. This feature can be interpreted as a remnant of intermediate-depth winter convection in the west-central Labrador Sea during recent years. In 2004 and 2005 the minimum potential temperature in the 27.72-27.75 kg/m^3 layer is found near the bottom of the layer.

Interannual changes in heat, salt, and geopotential

The changes in heat and salt from 1990 to 2000 were discussed by Lazier *et al.* (2002). Time series of the changes in heat, salt, and geopotential in selected pressure layers from spring and early summer AR7W surveys from 1990 to 2005 are shown in Fig. 9(a)-9(c). Each series is plotted as an anomaly relative to its 1994 value. Seasonal changes have been removed from the 0-150 dbar pressure range as discussed above.

The ranges of heat and salt content in the 0-2000 dbar layer in Fig. 9(a) and 9(b) are approximately 5 GJ/m^2 and 100 kg, respectively. A heat gain of 1 GJ/m^2 by this layer would increase its mean temperature by about 0.12^{o}C. An increase of 20 kg/m^2 of salt in the same layer would raise its mean salinity by about 0.01.

The heat content in all layers in the 0-2000 dbar range increased from 2004 to 2005. Following a 6-year increasing trend, the 2005 the 0-2000 dbar heat content was the greatest in the 16 spring and early summer AR7W surveys

The upper layer salt content shows more vertical structure and higher frequency variability than the heat content. The 0-2000 dbar salt content decreased in 2005 compared to 2004 because the upper 1000 dbar layer was fresher, but 2005 still gave the second highest salt content in the 16-year record.

Higher temperatures correspond to lower water densities and increases in buoyancy and geopotential. Higher salinities correspond to greater water densities and decreases in buoyancy and geopotential. Figure 9(c) shows the changes in geopotential relative to 1994 associated with the pressure layers in Fig. 9(a) and 9(b). A large increase in buoyancy and geopotential took place from 1994 to 1999-2000 as the upper 1000 dbar layer warmed while salinity remained relatively constant. Recent years have seen generally warmer and saltier upper-layer conditions, with only a weak residual positive trend in buoyancy or geopotential. The observed warmer and freshening in the upper 1500 dbar in 2005 both contribute to lower density and greater buoyancy and geopotential. Figure 9(c) also shows the equivalent changes in geopotential associated with altimeter observations of sea level. The sea level changes are largely explained by steric effects in the upper 2 000 m of the water column, with changes in the upper 1 500 m having the greatest effect.

Acknowledgments

Monthly mean surface air temperatures for Cartwright and Labrador data were provided by the Canadian National Climate Data and Information Archive, operated and maintained by Environment Canada. [http://climate.weatheroffice.ec.gc.ca/climateData/monthlydata_e.html]

Nuuk monthly mean surface air temperatures up to 2004 were provided by the Danish Meteorological Institute [http://www.dmi.dk/dmi/tr05_05_recommended2004.zip] as documented in Technical Report No. 05-05 by Cappelen et al. (2005). http://www.dmi.dk/dmi/index/viden/dmi-publikationer/tekniskerapporter.htm

Recent monthly mean surface air temperatures for Nuuk were provided by the Danish Meteorological Institute. [http://www.dmi.dk/dmi/index/gronland/verdensvejr-gron.htm]

The HadISST1 Global Sea Surface Temperature data set was provided by the Hadley Centre for Climate Prediction and Research, Met Office, Bracknell, UK. [http://www.metoffice.com/research/hadleycentre/obsdata/HadISST1.html]

Data from the NCEP Reanalysis were provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/.

MSLA altimeter products were provided by the French AVISO/Altimetry operations centre at the CLS Space Oceanography Division. [http://www.aviso.oceanobs.com/]

Climatological hydrographic data were provided by the U.S. National Oceanographic Data Center. [http://www.nodc.gov/]

Many staff and associates of Ocean Sciences Division (OSD) at BIO have contributed to the Labrador Sea programme. John Loder presently leads the associated OSD Ocean Circulation and Variability Programme. Allyn Clarke, Glen Harrison, and Igor Yashayaev have provided critical leadership to the surveys in recent years. These efforts, together with those of the officers and crew of CCGS Hudson, are gratefully acknowledged.

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Fig. 1. Map of the Labrador Sea showing the AR7W section, selected meteorological stations, and Ocean Weather Station Bravo. The circled area is referred to in the text as the west-central Labrador Sea.

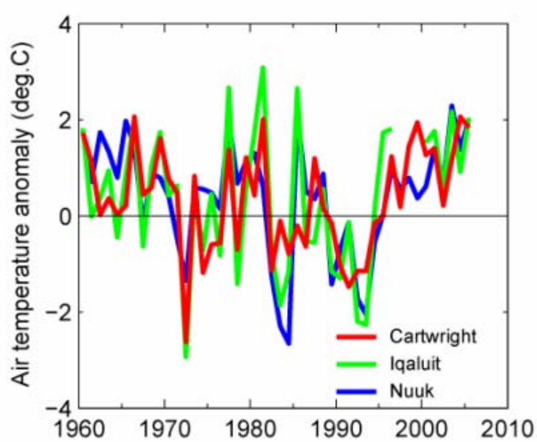


Fig. 2(a). Annual mean air temperature anomalies for 1960-2005 relative to a 1971-2000 normal for Cartwright, Labrador; Iqaluit, Nunavut; and Nuuk, Greenland.

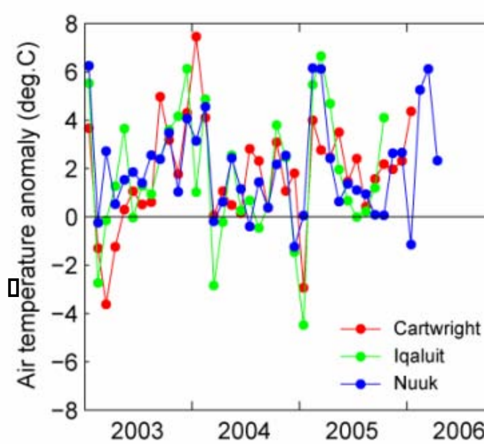


Fig. 2(b). Monthly mean air temperature anomalies for 2003-2005 as in Fig. 2(a).

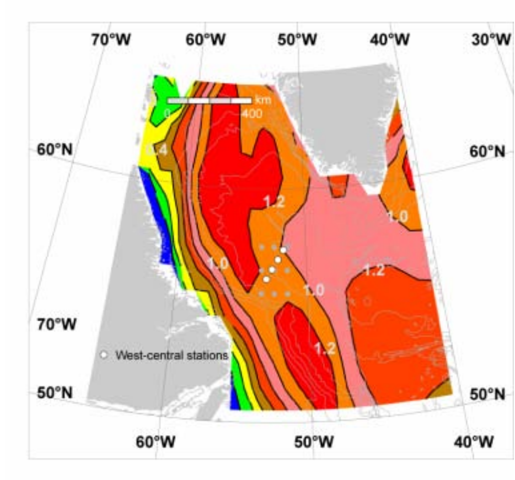


Fig. 3(a). Mean 2004 HadISST1 Labrador Sea SST anomaly (^{o}C). Hollow circles mark positions of four AR7W stations discussed in the text. Light grey circles are selected HadISST1 grid points.

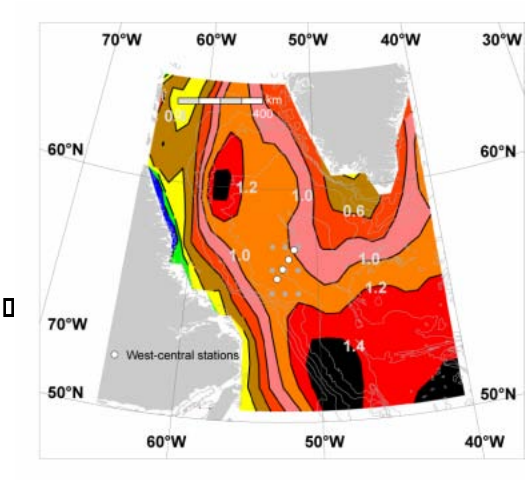


Fig. 3(b). Mean 2005 Labrador Sea SST anomaly (^{o}C) as in Fig. 3(a).

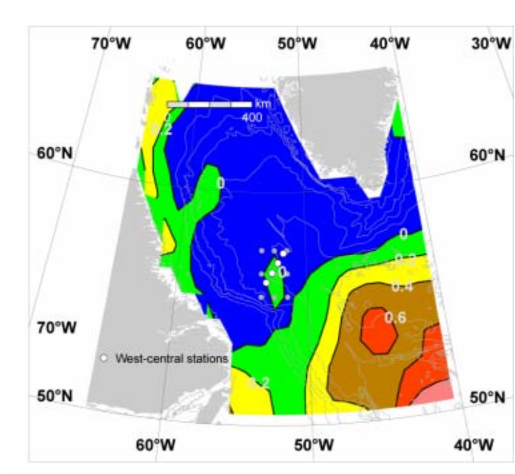


Fig. 3(c). Changes in annual mean Labrador Sea SST from 2004 to 2005 as in Fig. 3(a) and 3(b).

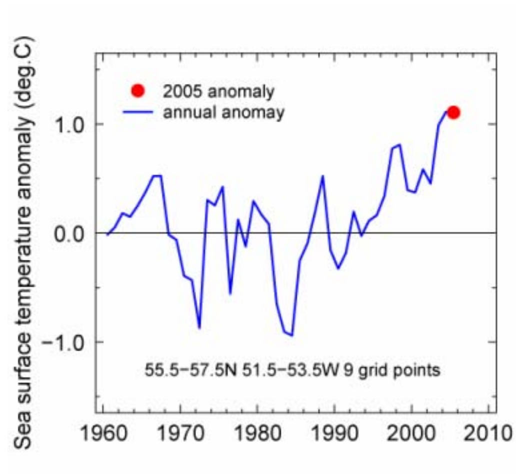


Fig. 3(d). Time series of annual SST anomaly averaged over 9 HadISST1 grid points centred at 56.5N, 52.5W in the west-central Labrador Sea marked in Fig. 3(a)-3(c). The normal value is 4.22^{o}C.

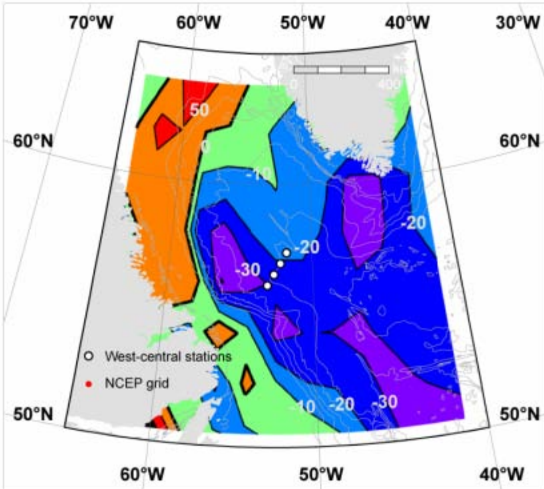


Fig. 4(a). 2004 annual mean Labrador Sea sea-air heat flux anomaly (W/m^2) from monthly mean NCEP/NCAR Reanalysis flux fields on a T62 Gaussian grid. Open circles mark selected AR7W stations.

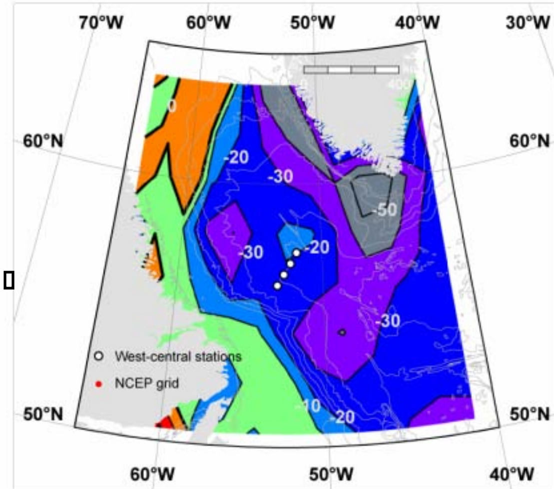


Fig. 4(b). 2005 annual mean Labrador Sea sea-air heat flux anomaly as in Fig. 4(a).

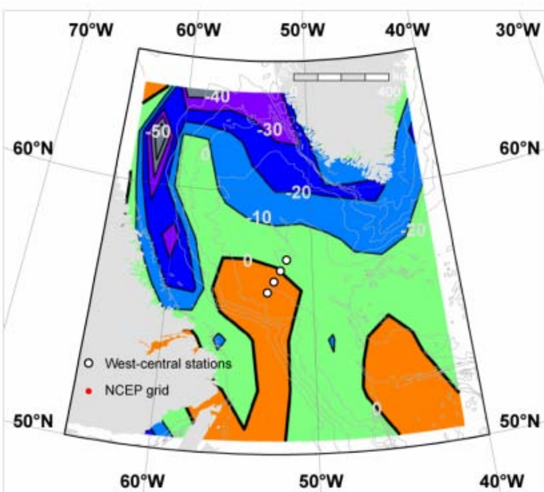


Fig. 4(c). Change in annual mean Labrador Sea sea-air heat flux from 2004 to 2005 as in Fig. 4(a) and 4(b).

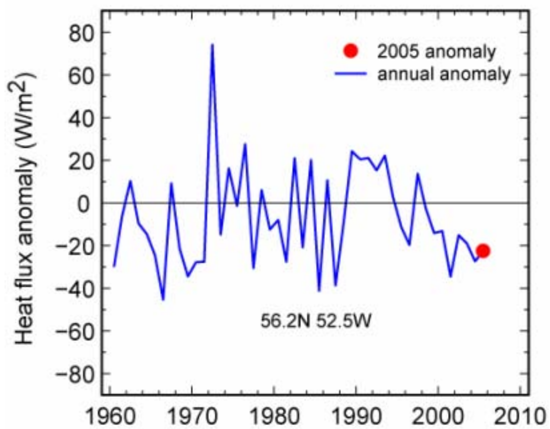


Fig. 4(d). Time series of annual sea-air heat flux anomaly from the NCEP/NCAR Reanalysis grid point at 56.2N, 52.5W in the west-central Labrador Sea. The normal value is 66 W/m^2.

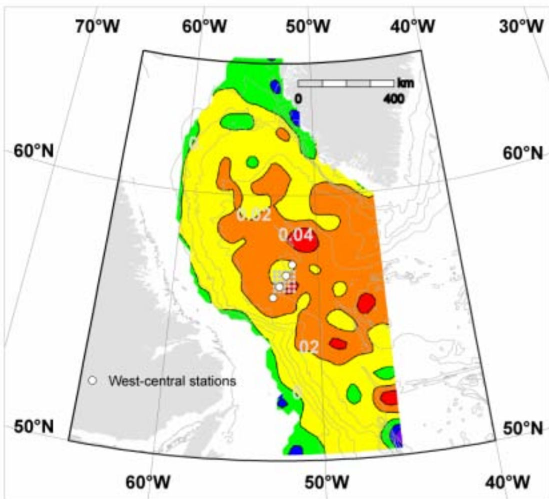


Fig. 5(a). 2004 mean Labrador Sea sea level anomaly (m) from the Aviso gridded MSLA product

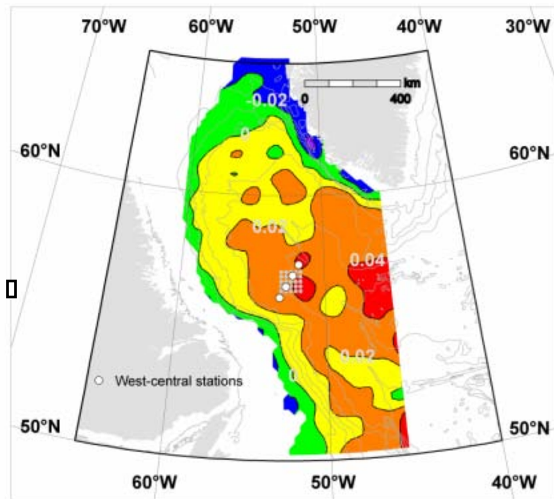


Fig. 5(b). 2005 mean sea level anomaly for the Labrador Sea as in Fig. 5(a).

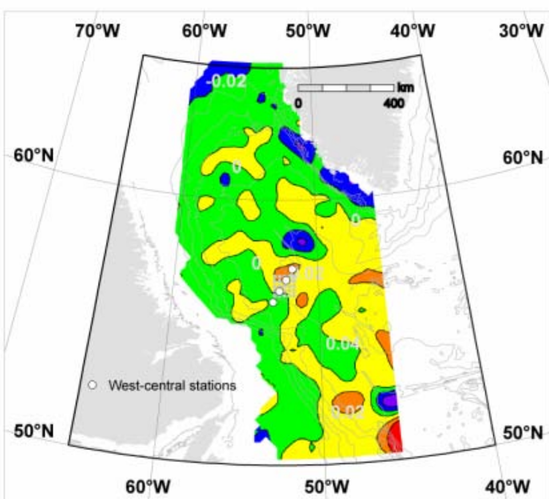


Fig. 5(c). Change in annual mean Labrador Sea sea level anomaly from 2004 to 2005 as in Fig. 5(a) and 5(b).

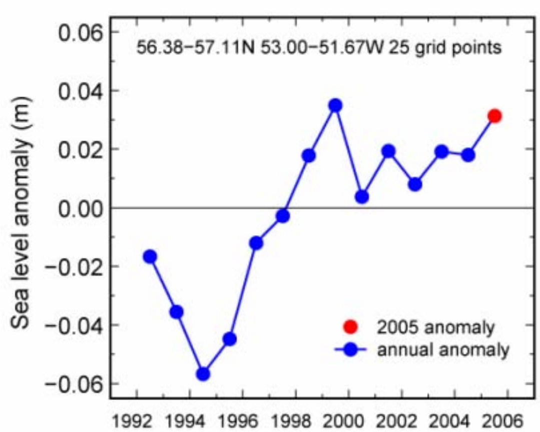


Fig. 5(d). Time series of spatially averaged annual mean SLA averaged near 56.7N, 52.3W relative to the 1993-2005 mean value.

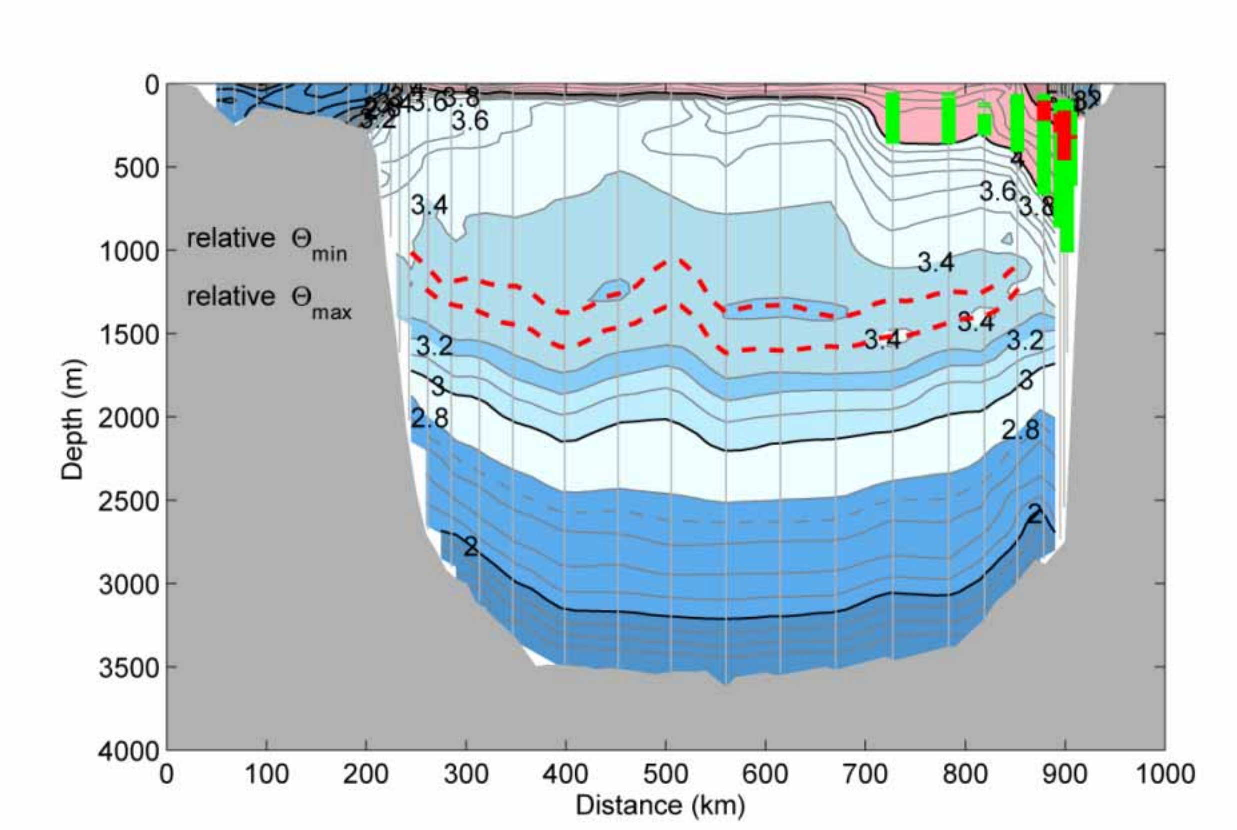
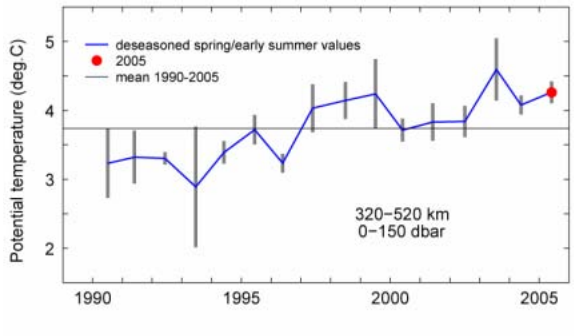


Fig. 6. Potential temperature (^{o}C) on the AR7W section in late May-early June 2005. Station positions are indicated by vertical lines. The dashed lines trace layers of relative minimum and maximum potential temperature. Colour highlighting marks stations and depth ranges showing Irminger Mode Water (green) and Irminger Atlantic Water (red) as defined in the text.



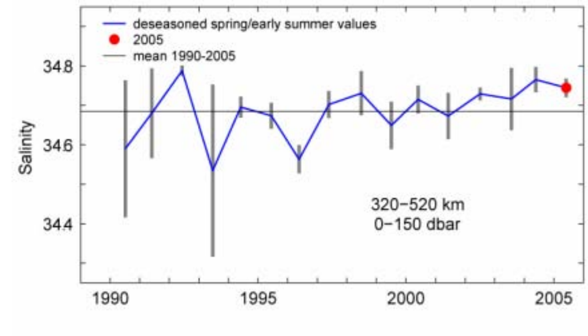


Fig. 7(a). Deseasoned 0-150 m potential temperature from the 320-520 km distance range for spring and early summer AR7W occupations. Error bars are among-station standard deviations for each survey.

Fig.7(b). Deseasoned 0-150 m salinity from stations in the 320-520 km distance range for spring and early summer AR7W occupations as in Fig. 7(a).

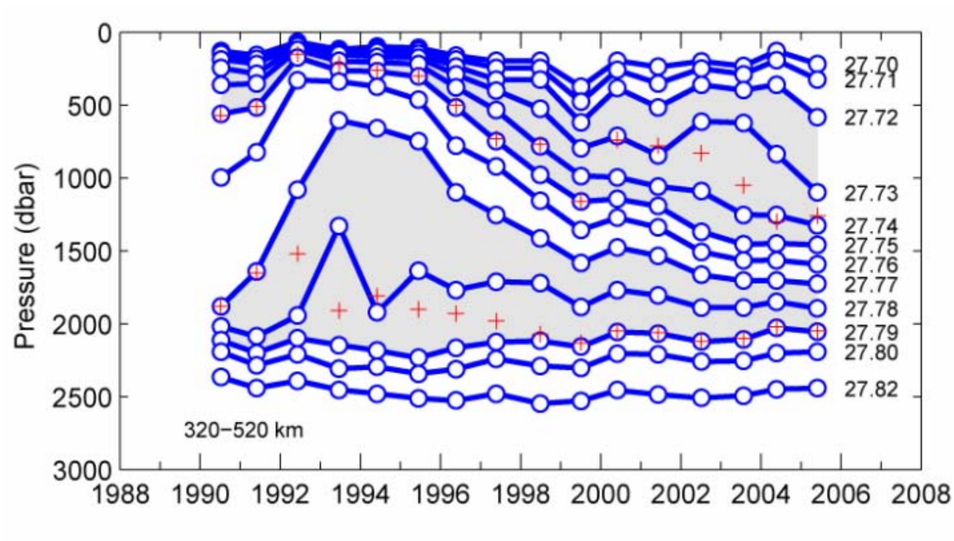


Fig. 8. Time series of pressure on selected potential density surfaces averaged over stations in the 320-520 km distance range for spring and early summer AR7W surveys from 1990 to 2005. Crosses mark pressures at minima in potential temperature in two shaded layers 27.72–27.75 kg/m^3 (upper) and 27.77–27.79 kg/m^3 (lower).

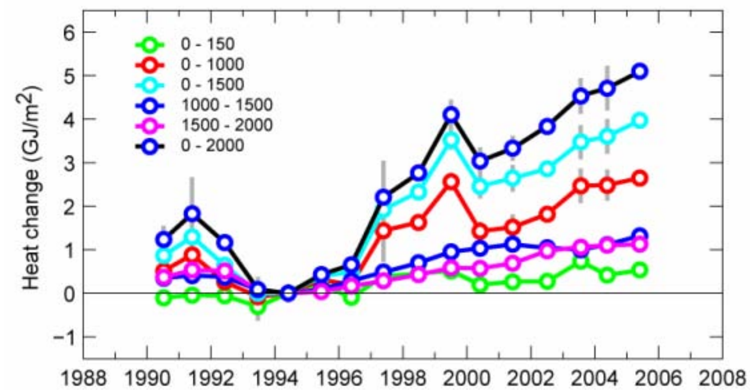


Fig. 9(a). Heat content in selected layers relative to 1994 from spring and early summer AR7W occupations. Values are averages over stations in the 320-520 km distance range. The legend gives the pressure ranges for each layer in dbar. Climatological seasonal effects in the 0-150 dbar pressure range have been removed.

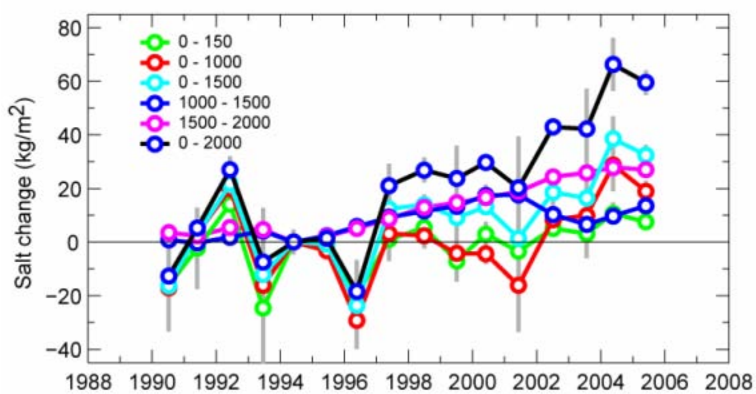


Fig. 9(b). Salt content in selected layers relative to 1994 from spring and early summer AR7W occupations averaged over stations in the 320-520 km distance range as in Fig. 9(a).

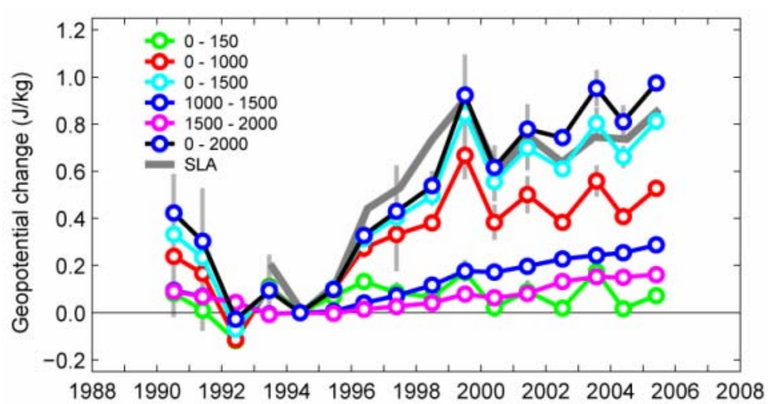


Fig. 9(c). Geopotential changes for selected layers from spring and early summer AR7W occupations as in Fig. 9(a) and geopotential changes associated with annual mean altimetric sea level anomalies (SLA) as in Fig. 5(d), all relative to 1994.